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MICROFABRICATION TECHNOLOGY FOR PHOTONICS

Cornell University

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13. ABSTRACT *(Maximum 200 words)*
This study identifies key research areas in the area of photonics microfabrication technology. Discussions are presented on optical non-linearity, bistability, fundamental problems in digital optical processing, generic micro-structures needed for integrated photonics and the fabrication technology used in their realization, equipment needed for such technology with quoted price ranges where available, major equipment for optional or future consideration and laboratory space and special service requirements. Keywords:

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TABLE OF CONTENTS

LIST OF FIGURES AND TABLES

MICROFABRICATION TECHNOLOGY FOR PHOTONICS-FINAL REPORT

I. Introduction

It is the purpose of this study to identify key research areas serving the overall objectives of the photonics center which could be addressed by micro-fabrication technology. The objectives of the center are primarily applied. That is, the center's purpose is to speed the transition from the results of basic research to realization of optical systems which satisfy the needs of the Air Force.

Major areas of current research at the center are digital optical information processing, analogue optical signal processing, and optical interconnections having microwave and even millimeter wave bandwidths. All of these are areas that are currently in rapid evolution as a result of emerging new materials, epitaxial structures, and certain key fabrication technologies. However, in none of these areas has any consensus of opinion arisen regarding the optimum material and device basis for a functional system.

From basic principles such as speed and potential for parallelism, a strong case can be made for the potential advantages of optics for computing(1), but at the present time finding a suitable optical analogue of the transistor is still the main subject of research. It is evident, then, that while some work can proceed on higher level problems such as special architectures, the development of actual systems will occur as the result of advances in the area of materials and devices. Plotting a course toward the center's objectives therefore requires a long view and recognition of the value of developing expertise and achievements in the central arena of current progress. Sections below will present discussions of optical non-linearity, bistability, and fundamental problems in digital optical processing, generic micro-structures needed for integrated photonics and the fabrication technology used in their realization, equipment needed for such technology with quoted price ranges where available, major equipment for optional or future consideration, laboratory space and special service requirements, rough manpower requirements, and local opportunities for university collaboration.

II. Non-linearity, and Bistability in Digital Optical Signal Processing

II.1 Introduction

Penetration of optics into the field of information processing is progressing through stages which have been identified as computer mainframe interconnects, module interconnects, board interconnects, chip interconnects, device interconnects, electro-optic logic gates, and finally all optical logic. At each stage, there are anticipated advantages over electronic methods. Common advantages of optical interconnects at all of the stages are large bandwidth and freedom from interference. At the stage of board interconnects, free space optics offers the advantages of increased programmability and parallelism. Beyond these advantages, however, is a basic one which has been discussed very recently by D.A.B. Miller.(2) The demands of small size and low switching energy for electronic logic elements lead to a high impedance for those elements. Communication links between them, however, have relatively low impedance--of order 50 ohms for transmission lines and a few hundred ohms for waveguides--so that transmission elements present an impedance mismatch to electronic logic elements. Optical emitters and detectors, on the other hand, inherently produce efficient impedance transformations. In the case of a detector, for example, a fixed amount of charge is produced per photon detected and this charge can be fed into a high resistance in order to give the required voltage for low bit error discrimination.

The interaction of light with matter is characterized by the index of refraction of the material, which can be field dependent and anisotropic as well as having both imaginary and real components. These components determine the absorption and the relation between frequency and wavelength for a propagating beam. For hybrid, i.e. electro-optic logic, one utilizes the field dependence of the components through an applied modulating field. An approach to all-optical logic is to obtain the modulating field by detection of a "control" beam of light. A device with integrated detector and modulator constitutes a self electro-optic device or "SEED"(3) . This approach has produced the lowest switching energies, but since detection implies the accumulation of charge, the speed of such a device is potentially limited in comparison with one in which the refractive index of the device material, and therefore the passage of a light wave, is directly affected by the presence of the control beam. Such a material is said to be intrinsically "non-linear" since the refractive index is not a constant but (to next order) is given by

$$n = n_0 + n_2 I \tag{1}$$

where I is the optical intensity. Characterization of a non-linear material is usually given in terms of $\chi^{(3)}$, the third order susceptibility, which is related to n_2 by

$$n_2 = \frac{480\pi^2}{c\, n_0^2}\chi^{(3)} \tag{2}$$

where n is in units of m^2/Watt and $\chi^{(3)}$ is in e.s.u.

The ultimate speed of the non-linear refractive index is limited by the relaxation time, τ, of the particular electronic energy transition giving rise to the non-linearity. Unfortunately, the coefficient of the non-linear term in Eq. 1 is small for suitably fast known materials, so that a cavity is often used to increase the effective intensity. The cavity, however, has its own response time or "filling time" which, for fast materials, becomes the limiting factor in the switching speed of the device. To reduce the energy storage necessary to achieve switching, what is needed is a material with a stronger (but still fast) non-linearity coupled with a low absorption so that the energy which needs to be stored in the cavity for switching can be reduced. Thus, in the discussion below of various nonlinear materials and effects, use is made of a figure of merit, M, given by

$$M = \frac{\chi^{(3)}}{\alpha \tau} \tag{3}$$

where $\chi^{(3)}$ is in e.s.u. and α is the absorption per cm. of the material.

The amount of speed needed in the switching elements depenas on the parallelism of the architecture. With sufficient parallelism, processing rates far exceeding those possible in conventional electronics could be achieved with response times as large as microseconds. While optics is considered to offer the physical potential for such exceptionally high parallelism, practical architectures implementing such parallelism for general computation are not yet available. Thus the optically non-linear materials and effects suitable for image processing will be different from those suitable for general purpose computation. The figure of merit given above therefore has to be applied loosely, with other factors such as response time, τ, and the particular application being considered additionally. To compete with electronics in a conventional architecture, the speed of optical switching elements has to be in the low or even sub-picosecond range.

Many optically non-linear materials, both organic and semiconductor, are being investigated as possible bases for logic devices. A major assessment of research on these materials by a panel of top researchers in the field was published in January, 1987.(4) Some of the key conclusions of this panel are summarized in the following section. The summary is followed by descriptions of the physical mechanisms underlying the most important optical nonlinearities in semiconductors.

II.2 Summary of the January, 1987 panel assessment.

Material in this section (II.2) is quoted or paraphrased from reference 4.

Among organic materials are some with very fast (femtosecond) response times, but none having simultaneously the strength of non-linearity found in semiconductors. Other important limitations for organics are related to physical and chemical stability, for example oxidation resistance and resistance to thermal degradation. The present level of development of organics for optical logic lags behind that of semiconductors. Nevertheless, because of their high speed, they are potentially very important. Table 1 lists some of the organic materials being investigated for their non-linear properties.

Table 1. Some organic non-Linear materials

Substituted and desubstituted acetylenes and diacetylenes
Anthracenes and derivatives
Dyes
Macrocyclics
Polybenzimidazole and polybenzobisoxazole
Polyester and polyesteramids
Polyetherketone
Polyquinoxalines
Pophyrins and metal-porphyrin complexes
Metal complexes of TCNQ or TNAP
Urea

Semiconductors, on the other hand, have the advantage for non-linear optics that they combine relatively good figure of merit with materials and device fabrication technologies that have already experienced much development effort. They are useful over wavelength ranges from 0.3 to 12 microns, and in the range of 1 micron, e.g. for GaAs and InP, it is possible to integrate electronic devices, optoelectronic devices, and laser diode sources with non-linear optical structures.

Another class of material for non-linear optics is glass doped with semiconductor(5). The small crystallite size (tens to thousands of angstroms) leads to a very rapid carrier decay time and the possibility of devices with picosecond switching speeds.

II.3 Nonlinear optical effects in semiconductors.

Achievement of optical bistability in semiconductor materials was reported for InSb in 1978(6) and GaAs in 1979(7). Subsequently, non-linearities at bandgap wavelengths have been investigated in multiple quantum well structures in material systems such as GaAs/AlGaAs, as well as in other non-linear bulk materials such as CdS, InAs, and HgCdTe(8). Multiple quantum well structures show enhancement of a number of non-linear effects at bandgap wavelengths(9), but effective utilization in switching devices is hampered by high background absorption(10), and it is not clear that there is a net advantage over bulk semiconductors with conventional heterostructures, which are easier to fabricate. However a new class of non-linearity in quantum wells, which has been called the QWEST effect has been shown to offer considerable promise(11). It operates at much longer than bandgap wavelengths and will be described later in this report.

Figure 1 is a diagram classifying by type the physical effects responsible for optical non-linearity which have been extensively studied. It also summarizes the materials in which they have been seen. Optical bistability and switching in all of these materials have been reported. In general, optical non-linearity arises in a material whenever the properties of electrons responsible for some of the dielectric constant of the material are affected by the intensity of optical illumination. Typical properties so affected are the number density of free electrons, their mass, their temperature, the energy level occupancy of free or bound electrons, and the lattice temperature. Changes in these properties can result in changes in both the absorption and the dielectric constant or index of refraction. Below is a discussion of the particular mechanisms responsible for nonlinearity in the semiconductors shown in Figure 1.

II.3.1 Nonparabolicity in InSb, InAs, GaAs and PbTe.

The earliest optical non-linearity found in semiconductors was due to non-parabolicity in the conduction band and was seen, in 1966, in InAs InSb, GaAs, and PbTe(12) at wavelengths around 10 microns. Recalling that the effective mass is inversely related to the curvature of the Energy versus k diagram,

$$m^* = \hbar^2 \left(\frac{\partial^2 E}{\partial k^2} \right)^{-1} \tag{4}$$

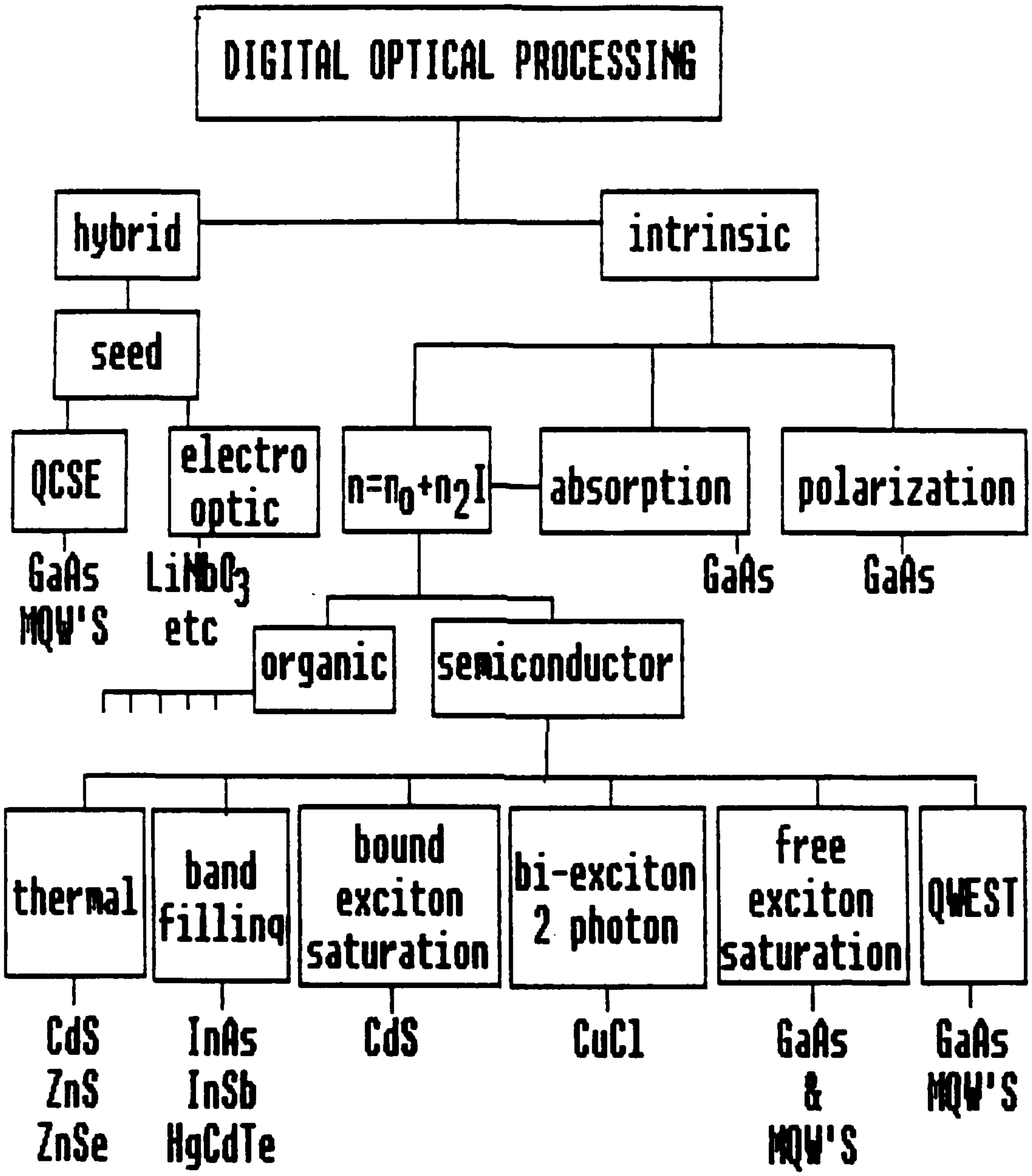

Figure 1. Schematic showing some of the effects and the materials studied for digital optical signal processing.

we see that "non-parabolicity" means that the effective mass is not constant but depends on the electron's energy within the conduction band. The inertial motion of free electrons in the optical electric field makes a contribution to the dielectric constant just as in a plasma. The contribution depends on the effective mass. To a degree dependent on the intensity of optical radiation the electrons become heated, meaning that they are distributed among higher energies in the conduction band where their effective mass is greater. With the average mass thus dependent on the radiation intensity, the contribution to the dielectric "constant" is also. The strength of this non-linearity is low compared to others which have followed as can be seen from Table 2, pg 21. The principal interest at the time of its discovery derived from its being the first non-linearity from non-bound electrons which offered new possibilities for varying its properties through doping, choice of material and temperature, etc. It was also much larger than the previous plasma non-linearities which were due to the effect of the radiation magnetic field on the motion of the electrons.

II.3.2 Band Filling in InSb, InAs and HgCdTe.

The first strong optical non-linearity, found in 1978(6), was the "band filling" or "dynamic Burstein-Moss effect" in InSb. The original Burstein-Moss effect was the slight shift in wavelength of the bandgap transmission cutoff, resulting from doping the semiconductor. "Dynamic" was the term added to the Burstein-Moss effect to describe the same change in absorption "edge" when it is caused not by doping but by changes in the electron concentration brought about by optical ionization of electrons across the band gap. Electrons introduced to the conduction band and not subsequently heated will occupy the lowest levels of the conduction band, preventing other electrons from being ionized into those same levels. Thus as the optical intensity increases, progressively higher photon energy is required to raise an electron from the valence band into an empty state in the conduction band. Therefore, if the incident radiation is initially at a wavelength corresponding to a steep part of the absorption edge, increasing its intensity will shift the edge to a shorter wavelength, dramatically reducing the absorption at the incident wavelength. This reduction of absorption then produces a change in the index of refraction through the fundamental Cramers-Kronig relation (T.S. Moss, Ref. 38, 1980):

$$n_a - 1 = \frac{1}{2\pi^2} \int_0^\infty \frac{\alpha \, d\lambda}{1 - \lambda^2/\lambda_a^2} \quad (5)$$

where n_a is the refractive index at a particular wavelength, λ_a.

The band filling non-linearity is strongest in small band gap semiconductors (and therefore at long wavelengths) since these have a lower density of states at the conduction band edge. Creation of a given density of electrons in the conduction band therefore fills the band to a greater energy, producing a greater shift. Also for reasons of state density, the contribution of holes filling the top of the valence band is negligible. In 1985, strong band filling non-linearities were also reported in InAs(13) and HgCdTe(14). The speed of the effect is determined by the interband recombination time. The shortest switching times seen are 10's of nanoseconds, but the intensities needed for switching are still among the lowest, making band filling one of the most promising approaches to optical computing with massively parallel architectures. However, since the wavelength must be closely tuned to the absorption edge which depends on the (temperature dependent) band gap, the effect is both temperature sensitive and limited to 90K or below. Development and demonstration of optical switching devices based on the band filling non-linearity has been a major focus of the group at the Heriot-Watt University at Edinburgh. A chronological bibliography of most of the work on the band filling non-linearity is given in reference (38).

II.3.3 Free Excitons in GaAs and AlGaAs/GaAs Quantum Wells.

Following the 1978 discovery of the band filling non-linearity was the discovery in 1979 of a strong non-linearity resulting from absorption by free excitons in GaAs(15). A free exciton is a hydrogen-like "atom" which can form between a free electron and hole. The binding energy of this pair is only a few millivolts, so that excitons have appreciable lifetime only at low temperatures where thermal agitation cannot "ionize" or break them apart. The free exciton nolinearity was thus studied exclusively at low temperatures until 1982 when the same nonlinearity was found in quantum wells(16). In quantum wells, the two dimensional confinement of electrons and holes within wells of the same magnitude as the exciton diameter prevents the excitons from being so readily ionized--that is, the binding energy is increased to about 10 millivolts. While this value is still below kT at room temperature (25mV), nevertheless noticeable peaks in the absorption spectrum due to excitons can be observed in quantum wells at room temperature. Quantum wells were thus touted as offering considerable advantage over bulk GaAs until 1985 when it was shown that non-linearity due to excitons in bulk GaAs also exists at room temperature at about 2/3 the strength of that in quantum wells(17).

The actual mechanism by which free excitons produce optical non-linearity explains how they can do so even when kT is greater than the binding energy of the excitons. The elevation of an electron from the valence band into an excitonic state (where its energy is just below the conduction band) has a strong optical cross section. Thus when photons are incident with the energy required for the elevation, most of their absorption is due to such transitions. Once formed, an exciton immediately (in less than 0.5 picosecond) becomes thermally ionized meaning that it splits into a free electron in the conduction band and a free hole in the valence band. At high optical intensities, the electron-hole plasma so created is dense enough to provide significant occupation of the space within the exciton and thereby to screen the Coulomb attraction which binds the exciton together. This reduces the opportunity for further exciton formations. High optical intensity thus has the effect of reducing absorption, as it does in the case of the band filling nonlinearity. Again by the Kramers-Kronig relation (Eq.4) the change in absorption produces a change in the index of refraction. While the formation of the screening plasma is very rapid, its disappearance occurs by electron-hole recombination which requires about 20 nanoseconds following termination of the radiation. The switch-off speed of the free exciton non-linearity is therefore too low for the requirements of serial architecture.

II.3.4 Bound Excitons in CdS.

A step up in switching speed was achieved in 1983 with the discovery of non-linearity due to bound electrons in CdS(18). At temperatures in the LHe range, excitons can become bound to impurity atoms in the crystal. Bound excitons have a stronger optical interaction and their recombination is radiative, occurring in CdS at one nanosecond rates. The mechanism causing nonlinearity in bound excitons is different from free excitons, and results in the non-linearity taking place at much lower intensities. The density of bound excitons cannot exceed the impurity density. As this density is approached by raising the incident illumination, absorption by bound exciton formation must decrease. Thus while the mechanism is different, "saturation" of the absorption also takes place here and by the Kramers-Kronig relation (Eq.4) produces a change in the refractive index.

II.3.5 Biexcitons in CuCl.

A biexciton is an excitonic molecule, i.e. the bound state of two excitons, and can be generated by the simultaneous absorption of two photons. Optical bistability based on this occurrence was theoretically predicted in 1981 and realized in 1983(19). Its switching time is in the four hundred picosecond range. As with bound excitons, the effect takes place at temperatures in the LHe range. It is hampered by background absorption due to a tail on the nearby absorption peak of the ordinary excitons. This background absorption necessitates an intensity for bistability of order 10 Megawatts/cm compared to 100 W/cm2 for band filling in InSb and 10 W/cm for bound excitons in CdS.

II.3.6 Intervalence Band Transitions in p-type HgCdTe, GaAs & Ge

This nonlinearity was first reported in 1983 for HgCdTe(20), and subsequently in 1985 for GaAs and Ge(21). In p-type material hole transitions can be optically induced between the heavy hole and the light hole band thereby changing the average effective mass of the holes. Just as in the case of nonparabolicity, changing the average effective mass of free carriers changes their contribution to the susceptibility. In the case of HgCdTe, the transition between hole bands contributes some additional changes in susceptibility due to the saturation of absorption. As the light hole band becomes more densely populated at high intensity, transitions back to the heavy hole band become more probable which decreases or "saturates" the absorption and changes the dielectric constant through the Kramers-Kronig relation. This non-linearity exists at room temperature at a wavelength of 10 microns, and has a switching time on the order of 0.1 picosecond. The strength of the nonlinearity and its figure of merit are compared with other non-linearities in Table II.

II.3.7 Thermal Non-linearities in ZnSe, ZnS & CdS.

Optical bistability due to a thermal mechanism was reported in 1983 for interference filters made on ZnS and ZnSe(22,23) and on CdS in 1984(24). The band gap of semiconductors decreases slightly with temperature. Thus if light is incident at a wavelength on the steep part of the transmission cutoff at the band gap energy, the absorption will be a function of temperature. Absorption of high enough incident intensity will raise the temperature, increasing the absorption and changing the dielectric constant. Operation of non-linear interference filters based on this effect depends heavily on the design of the filters. In particular, the switching time depends on the substrate thermal conductivity while the switching energy depends on the spot size(23,25). Optimization of these parameters is still under investigation at Edinburgh. Operation at room temperature is possible, though stability of the ambient is obviously important as it is for most of the band gap resonant effects. Through choice of material, a wide range of wavelengths is available including the visible. In general the effect seems most suited to parallel array processing.

II.3.8 Two Photon/Free Carriers in HgCdTe.

In this effect, reported in 1985(26), photons are incident at an energy well below the band gap. Free electrons are generated across the band gap by simultaneous absorption of two photons. Non-linearity arises both because of the contribution of the free electrons and because of band filling which reduces the absorption, but the former is the dominant effect. Because the two photon absorption is weak, the magnitude of the non-linearity is 10e-4 times smaller than for band filling in InSb, with only comparable speeds.

II.3.9 Impurity Scattering in Si and HgCdSe.

This non-linearity, reported for Si in 1986(27), results from the dependence of impurity scattering rate on electron temperature. Free electrons are clustered around the attractive potential of ionized donor impurity atoms. This partially screens out the field responsible for the impurity scattering. When the temperature of the electrons increases due to heating by an intense incident radiation, the clustering is reduced, and consequently the scattering increases and conductivity decreases. Through a Kramers-Kronig integral relating the conductivity to the dielectric constant, the dielectric constant is also affected. Relaxation time for the effect is in the picosecond range, but the magnitude of $X^{(3)}$ is 5e-10 which is small compared to some others considered in this report (see Table II).

II.3.10 Interband Population Modulation in HgTe.

One of the strongest high speed nonlinearities known was reported in HgTe in 1987(28). HgTe is a semiconductor with a zero-energy bandgap. Thus at any finite temperature, the Fermi function distributes some electrons from the top of the valence band into the conduction band creating an electron-hole plasma whose density depends on the electron temperature. The plasma density again is related to the dielectric constant and can be changed by the effect of the incident radiation heating the electrons. The wavelength employed to investigate the effect was

10.6 micron simply because it is available from a CO_2 laser(28), but a range of wavelength is possible for the effect since the electronic interaction is simple heating rather than a resonant absorption. The relaxation time is about 5 psec. A salient feature of this non-linearity is the very high power density that can be reached without saturation of the effect. This results from the fact that the plasma density continues to increase with temperature, and there is no screening effect as, for example, in the case of excitons.

II.3.11 Intersubband Transitions in AlGaAs/GaAs Quantum Wells

Though non-linearity from intersubband transitions was proposed by Yuen in 1983(29), experimental results were first achieved in 1985 by Lawrence West and S. J. Eglash who called it QWEST for Quantum Well Envelope State Transition(30). Currently at AT&T Bell Laboratories, West also announced in 1987 his plans to develop an all optical bit serial supercomputer with one million gates based on the QWEST effect(11). His effort probably represents the most advanced current program aimed at practical development of a serial type optical computer with potential speed advantages over electronics.

Refractive non-linearity in the QWEST effect results from saturation of the absorption and the Kramers-Kronig relation. Electrons are present in the lowest subband due to donor doping. They can be raised to some higher subband by absorption of resonant radiation, but as the distribution among the levels becomes uniform at higher intensities the net absorption is reduced. The optical interaction is strong since the dipole moment between states is distributed over distances of the order of the quantum well size which is much larger than atomic dimensions. Even though the transition is between energy bands, it is still relatively narrow since the energy difference between bands is constant for all k vectors, and the k vector doesn't change much during an optical transition. The bands overlap, however, meaning that relaxation can result from a phonon interaction which changes k without much change in energy followed by rapid cascading within the lower band.

The approach to QWEST system fabrication is markedly different from bandgap resonant effects in that the QWEST device will use longer (10 micron) wavelengths. The system "wiring" will be waveguides with conventional two dimensional integration except for the use of grating couplers for chip-to-chip interconnects through space. The speed advantage over state of the art electronics would derive mainly from the higher bandwidth of waveguides, the free space interconnects, and from the computer's reduced size which would be 1 cubic centimeter in the first versions, and ultimately 1 cubic millimeter. Thus, worst case signal propagation times across the computer would be a few hundred picoseconds in the early versions. West presents strong arguments for the approach, pointing out that the QWEST effect has the requisite speed (sub picosecond) and is relatively temperature insensitive, and that the use of longer wavelengths enables micron instead of submicron waveguides and avoids light scattering by edge roughness. Wavelength can in fact be engineered between 10 and 3 microns by design of the quantum wells. A possible disadvantage for Air Force applications would be the necessity to use a CO_2 laser for the optical power source. In the early versions this source would have to deliver power up to 10 kilowatts, but ultimately only 10's of watts would be needed which can be obtained from a laser less than one foot long. West is currently working on measuring the speed of the effect, developing the grating couplers which must be deeply grooved for strong coupling per grating line and chirped for producing a gaussian wavefront. and on developing waveguide crossovers using microwave frequency models. Construction of the computer is still years away, but he makes the claim that a direct path to its creation is known today.

II.3.12 Mode Switching Bistability

Another important development for serial computers report is the demonstration, by researchers at Cornell University, of optical bistability based on mode switching in semiconductor lasers.(31) By switching modes rather than total optical power, there is no accompanying change in charge distribution, so the switching can be expected to be faster. Like QUEST, this effect also lends itself to two dimensional, planar integration. It has the advantage that the optical source is integral to the device, but also the possible disadvantage of shorter wavelengths. The shorter wavelengths will require submicron waveguide dimensions with much smoother edges to avoid scattering the light. An RADC/NSF funded program is under way at Cornell to develop elementary logic circuits based on the effect.

II.3.13 Summary and Comparison of Semiconductor Non-linearities.

As mentioned previously, choice from among the various effects for system development depends on many design and fabrication considerations and cannot be made simply by straightforward choice of some figure of merit. Nevertheless, Table 2, below, lists some of the key performance characteristics of some of the semiconductor non-linearities described above. The next to last column is the power needed to saturate the effect, while the last column is a quantity which is proportional to the maximum possible perturbation of the dielectric constant. The table comes from reference (28) except for the data on QWEST which is from Lawrence West's thesis at Stanford University, July, 1985.

Table 2. Comparison of Semiconductor Nonlinearities

Year	Medium	Nonlinear mechanism	$\lambda(\mu m)$	T(K)	$\chi^{(3)}$(esu)	$\alpha(cm^{-1})$	τ(s)	$\frac{\chi^{(3)}}{\alpha\tau}\left(\frac{esu}{cm.sec}\right)$	$\chi^{3}P_{sat}\left(\frac{esu\ w}{cm^{2}}\right)$
1966	n-InSb	nonparabolicity	10.6	2	2×10^{-7}	2	4×10^{-12}	3×10^{-4}	> 0.2
1969	Ge	valence electron	10.6	300	1×10^{-10}	10^{-2}	1×10^{-14}	1×10^{6}	> 10^{-2}
1978	InSb	band filling	5.4	77	0.3	70	4×10^{-7}	1×10^{4}	30
1982	GaAs/AlGaAs	free exciton	0.84	300	4×10^{-2}	1.2×10^{4}	2×10^{-8}	170	400
1983	p-HgCdTe	intervalence band	10.6	300	8×10^{-6}	48	2×10^{-13}	8×10^{5}	8
1985	HgCdTe	band filling	10.6	77	5×10^{-2}	8	3×10^{-8}	2×10^{5}	5
1985	p-GaAs	intervalence band	10.6	300	1×10^{-6}	5×10^{3}	5×10^{-13}	400	> 1
1985	GaAs/AlGaAs	QWEST	8.0	300	2×10^{-3}	2.8×10^{4}	4×10^{-12}	1.7×10^{4}	>2000
1986	n-Si:P	impurity	10.6	300	3×10^{-7}	700	1×10^{-12}	430	> 0.3
1987	HgTe	interband	10.6	300	1.6×10^{-4}	3.4×10^{3}	5×10^{-12}	9×10^{3}	>160

III. Fundamental Problems in Digital Optical Signal Processing

Paralleling the investigation of new non-linear optical effects for digital processing, there have been a number of separate studies of the fundamental problems which will be encountered in the construction of real systems based on these effects. The earlier efforts concentrated on power requirements and the resulting thermal problems.(1,32,33) More recently, a paper has been written which adds to the power considerations a detailed discussion of other, specific, limits imposed by the use of optics. This paper, by M.E. Prise et al(34), published in 1988, establishes relationships between optical properties of non-linear devices (inherent gain, differential transmission, and contrast), system properties (system transmission and accuracies) and computational properties (cascadability, fanin, and fanout). Figures of merit are derived that show what makes a good device, and the minimum requirements for a device useful in digital processing are stated. Prise et al also consider the requirements for interfacing non-linear optical devices with free-space optical systems. Isolation is needed to prevent unwanted feedback between the different arrays in the system. Different inputs to a device have to be in different orthogonal modes because, otherwise, interference would prevent reliable switching. They also investigate the connectivity of free-space optics. Diffraction and aberrations are found to limit the channel capacity of single-lens systems. The idea that a completely arbitrary interconnect can be implemented using volume holograms is shown to be unrealistic in an optical system interconnecting large numbers of small devices.

The conclusion of this 1988 paper by Prise et al is a list of requirement:: and problems for the different areas involved in building a digital optical system. This list is reproduced in the following(34):

"Parallel Architecture has to deal with the following issues:

For not inherently parallel problems, we have to learn how to map them on a very wide pipeline and how to avoid registering (breaking of the pipeline).

We want an architecture using devices with low fanin and fanout. Furthermore, all devices across an array should be used with the same constant fanin and fanout.

With current devices, architectures relying on large fanin or fanout are unsuitable: the accuracy requirements for the system become so tight that they defeat the idea of digital computing. Also, devices suffering from critical slowing down would require long switching times in such an environment.

Since the number of devices we can interconnect scales with the regularity of the interconnect, the interconnects will have to be as regular as possible.

An architecture which relies on synchronous interconnects allows the use of pulsed logic.

An efficient architecture can probably compete with electronics if we have devices with similar power dissipation and switching times.

Not all of the following requirements for non-linear optical devices are mandatory, but they should serve to judge the computational merits of a proposed device:

The devices must be infinitely cascadable and they must provide a fanin and fanout of at least two (including system losses). Further, they must allow construction of any Boolean function (complete logical cover).

The devices must have multiple input ports (or support multiple modes), to allow isolation and lossless beam combination, and to avoid interference problems.

The energy dissipation must be low (at least comparable with electronics).

The device must be small. If we get near to the quantum limit, it pays to work farther out in the infrared.

The device must be integratable into relatively densely packed two-dimensional arrays. Reliable semiconductor technology is highly developed for electronics and opto-electronics, and can be modified for many non-linear devices. The homogeneity of the devices on a two-dimensional array, yield, reliability and other practical questions have to be addressed.

The device should not drift with temperature or other environmental disturbances. Thermal engineering will be extremely important if we want to have high-speed, high-bandwidth systems. This favors temperature-tolerant devices. In any case, efficient cooling systems have to be devised.

Devices without internal feedback (transmission independent from transmitted power supply beam) do not rely on critical biasing, nor do they exhibit critical slowing down. They are, therefore, highly desirable, since they reduce the system accuracy required.

Devices with absolute gain ease system accuracy requirements. For a fanin and fanout of 2 only a small gain is required, depending on the contrast and system losses. High absolute gain is, in many cases, not an advantage.

As high a contrast as possible is desirable, but not at the expense of transmission (of power to the next stage).

The development of devices which threshold with respect to a local reference would alleviate the requirements on system accuracy. Similarly, local input renormalization before each threshold operation is desirable.

Generally, NOR-gates look better than AND-gates, since they have minimum threshold. Furthermore, a computer built out of NOR-gates does not need to use dual-rail logic.

At the current state of development opto-electronic devices, where some of the energy is provided electrically, may be favoured due to a lack of optical power supplies (lasers) for powering large arrays. This may change in the future (18).

Although there are huge amounts of literature on optical computing, the optical power supply (needed for passive switching elements) is surprisingly seldom discussed:

We need powerful lasers at the wavelength of a strong optical non-linearity(18). For a reasonably large computer the cost per watt of laser light deserves serious consideration.

For pulsed logic the laser should produce pulses with gigahertz rates.

For critically biased devices (and to a smaller degree for all other devices as well), we need an accurate array generator to illuminate large arrays of the devices. Alternatively, we need large two-dimensional arrays of equal lasers.

Of course, we have again also to consider questions like reliability, drift, accuracies, etc.

The optical interconnects for a parallel optical computer have the following properties:

For small devices (power consumption!) accurate model imaging over a large field is required do minimize coupling losses. Therefore we need telecentric systems - preferably diffraction limited, with a large field and low geometrical distortion.

To have the means for preventing back-propagation (isolation), and to combine all of the different inputs losslessly, we have to couple into different modes of a device. Also, we do not need interferometric precision in alignment of such a sytem.

If temporal stacking is to be used, then the path lengths must be controllable to within one pulse length. This is relatively easy with single-lens imaging system.

For ultrafast pulses, it is preferable to use refractive and reflective components (lenses, mirrors, etc.) instead of diffractive components (holograms). The chromatic aberration is easier to compensate. Fast pulses, incidentally, may be used even is systems with comparatively long cycle times.

Since small devices are desirable for low power dissipation, some optical tricks, such as pupil division become difficult to implement (for multiplex rates greater than about 4). Similarly, operations such as magnification and demagnification become difficult, since they screw up the mode patterns.

Although the authors have no conclusive proof, we believe that optical free-space random interconnects can be used for very small numbers of devices. In all the schemes for achieving space variance by multiplexing discussed, the number of devices is reduced by a factor of M, where M denotes the degree of space variance. Since the computing power scales with the number of possible parallel operations, a very low degree of space variance is desirable. There seems to be a very basic trade-off between the degree of space variance and the degree of parallelism."(34)

Of significance to this report is the conclusion of Prise *et al* that "architecturally there seem to be two approaches: fast sequential systems having architectures similar to present electronic systems, and parallel synchronous pipelined computers with novel architectures." The sequential approach "*requires research on ultrafast, ultralow switching energy devices and on the problems associated with waveguide random interconnects*". For parallel systems we note that the architectures must be *novel*, i.e. new and untried, and if efficient, "can probably compete with electronics *if (one has) devices with similar power dissipation and switching times*." (All emphasis added.) It is most interesting that many of the requirements of the necessary novel architecture such as low fanin and fanout, constant across the array and having regular interconnects, are specifically addressed by a "folded," parallel architecture currently being proposed by A. Huang(35) who calls it "Computational Origami."

IV. Generic Microstructures and Fabrication Technology for Integrated Photonics.

In Figure 2 are shown the cross sections of three different types of optical strip-waveguide which could be fabricated on the surface of a semiconductor or dielectric material.

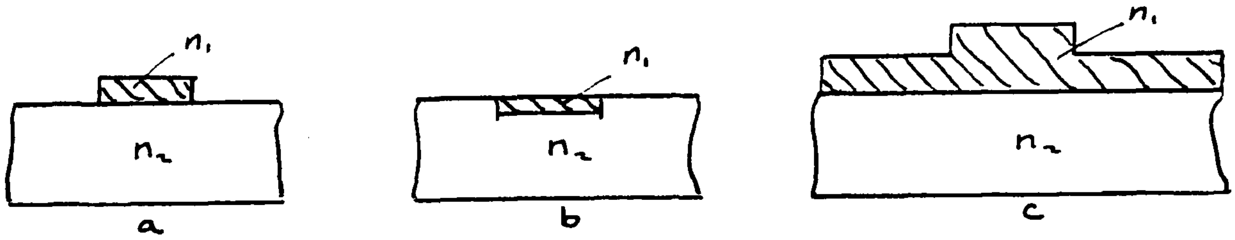

Figure 2. Cross section of some strip waveguide structures: a. Ridge guide; b. embedded strip guide; c. rib guide.

Structures a and c would be made by etching through a surface mask formed either of photoresist or some other suitable material which has been patterned in a previous step using photo (or electron beam or x-ray) resist. Structure b would be made by diffusion or ion implantation also through a surface mask. The cross hatched areas have higher index of refraction than the surrounding materials so that light is guided through the structure by total internal reflection.

Figure 3 is a micrograph(37) of an actual integrated laser structure based on waveguides of type c having an added metal layer on top of the rib which is used to provide current to the lasers. Lasing takes place in the material <u>under</u> the guide layer corresponding to the n2 region of Figure 2. The overall structure consists of three intersecting laser cavities each with one mirror formed by cleaving, and one formed by etching deeper into the n2 material than was necessary to form the guide. Each of the etched mirrors can be identified as one of the walls of the more deeply etched rectangles visible in Figure 3. The cleaved mirror of the "main laser" is visible as the forward end of the approximately 5 micron wide rib across the center of the figure.

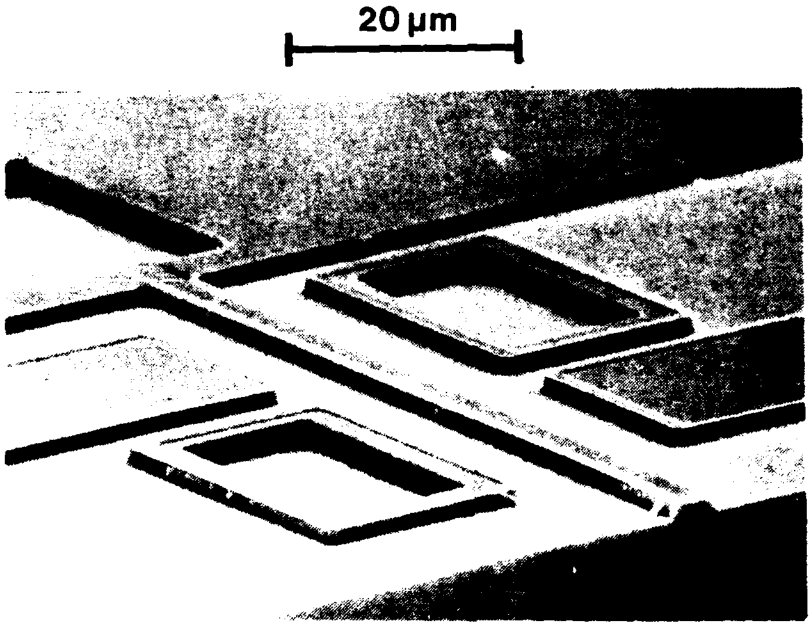

Figure 3. SEM photograph of a structure consisting of three integrated lasers(37).

Figure 4 shows a prototype design(11) of a logic gate based on the QWEST effect which similarly consists of intersecting cavities. Instead of laser material, the material inside the cavities (hatched areas in the figure) consists of an optically non-linear GaAs quantum well structure. Consequently the resonant wavelength and therefore the transmission through the cavities at a particular wavelength is a function of the intensity within the cavities. The mirrors here are more sophisticated, consisting of alternate Ge and AlGaAs or ZnSe sections forming interference-type reflectors. Other key integrated elements present are corner reflectors, beamsplitters, and cross-overs which are further detailed in Figure 5.

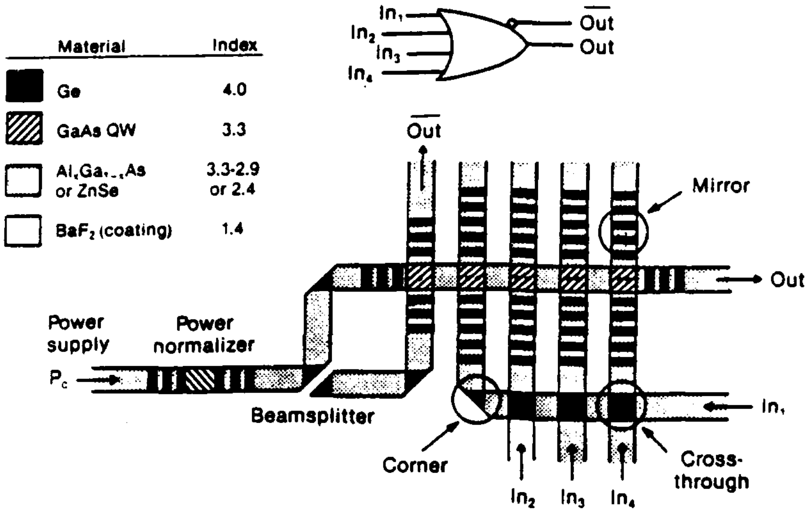

Figure 4. Prototype design of a logic gate using various optical components.(11)

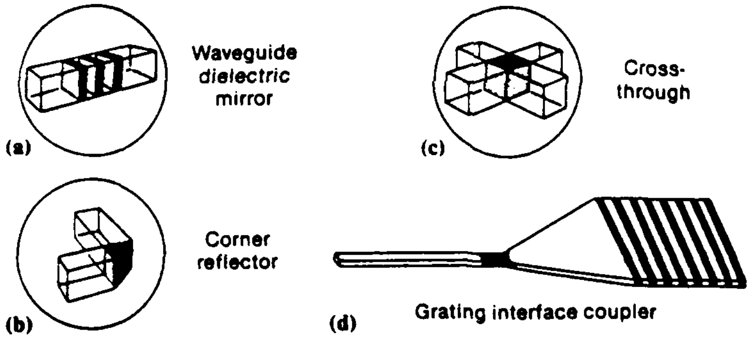

Figure 5. Various components being developed for integrated optical computers: (a) a waveguide 90-percent reflecting mirror constructed of alternating quarter-wave layers of zinc selenide and germanium etched across the full waveguide; (b) a waveguide corner turning the infrared light at a right angle by total internal reflection within the germanium prism; (c) a cross through with a higher index medium containing the light in the waveguides across the boundary, allowing signals to cross in one plane; (d) the coupler between the small waveguides and the external beams, consisting of a taper up to a large dimension (75 to 100 micrometers) grating, which couples light out normal to the surface in a Gaussian profile beam for coupling to lenses or to other boards directly above or below.(11)

Fabrication of the structures in Figures 4 and 5 would proceed something like the following:

(1) Growth by MBE or MOCVD of an AlGaAs layer followed by growth of the AlGaAs/GaAs quantum well layers. The first AlGaAs layer is intended to provide the etch stop used in step (7).

(2) In this step an ion implantation mask layer is formed using polyimide. To form the implantation mask, polyimide is first spun on. Next a layer of titanium is evaporated over the polyimide, and a layer of photoresist is spun over this. The resist is exposed to form openings through the resist in areas where the waveguides will be located. The titanium is then etched from these openings. The resist is then removed. Using the remaining titanium pattern as a mask, the polyimide is etched through to the wafer surface using an oxygen plasma. (Ti is resistant to the O2 plasma.)

(3) Implantation of protons through the polyimide openings is then performed. The purpose of this implantation is to disorder the quantum wells in the areas which are to be waveguides. The implantation is followed by removal of the titanium and of the polyimide, and then by a flash lamp anneal of the implant which will tend to form a uniform AlGaAs crystal in the implanted quantum well areas.

(4) In this step a mask for CAIBE etching of slots for the Ge mirrors and corner inserts is formed. First nickel is deposited. Photoresist is then spun over this and patterned with openings where the mirrors and corner inserts are to be. The nickel is etched through in these areas, and the photoresist is removed. Using the nickel pattern as a mask, the slots are then etched using CAIBE and the nickel is removed by wet etch. (Ni is resistant to Cl.)

(5) Germanium is then evaporated over the entire surface with a depth sufficient to fill the grooves. Following this a photoresist mask protecting the Ge in the grooves is formed. Ge is then etched from the remaining areas, and the photoresist removed.

(6) In a procedure similar to step (4) a mask is formed for CAIBE etching of the waveguide patterns, etching is performed, and the mask removed.

(7) In order to act as guides the waveguide patterns formed in step (6) must be provided with a substrate which has lower index of refraction than the AlGaAs guide material. Since the original GaAs substrate has a higher index, it must be removed. This can be done by first inverting and cementing the patterned surface on a low dielectric material to provide support, and then wet etching the GaAs substrate off using the original AlGaAs epi-layer as an etch stop.

The two most important technologies enabling the fabrication of integrated optical circuits of the above type are Molecular Beam Epitaxy (MBE) growth of the quantum wells, and Chemical Assisted Ion Beam Etching (CAIBE) of the mirrors and waveguides. The MBE technology required is at, but not beyond, the present state of the art. CAIBE is a relatively new technique, pioneered at Lincoln Laboratory (36), which is just now reaching the stage where it could provide the critical dimensions needed for mirrors and low loss waveguides. Most critical for integrated optical circuits is the possibility of forming smooth, perfectly vertical surfaces in order to avoid scattering losses at the mirrors and waveguide walls. Interference mirrors also need lateral tolerances which are fractions of a quarter wavelength which presses both the lithography and the etching technologies to their limits. A dry etching process, CAIBE achieves such critical dimensions using a combination of directed argon ions and chlorine molecules, as shown in Figure 6. Figure 7 shows the type of etching aspect ratios which have been achieved at Lincoln Laboratory.

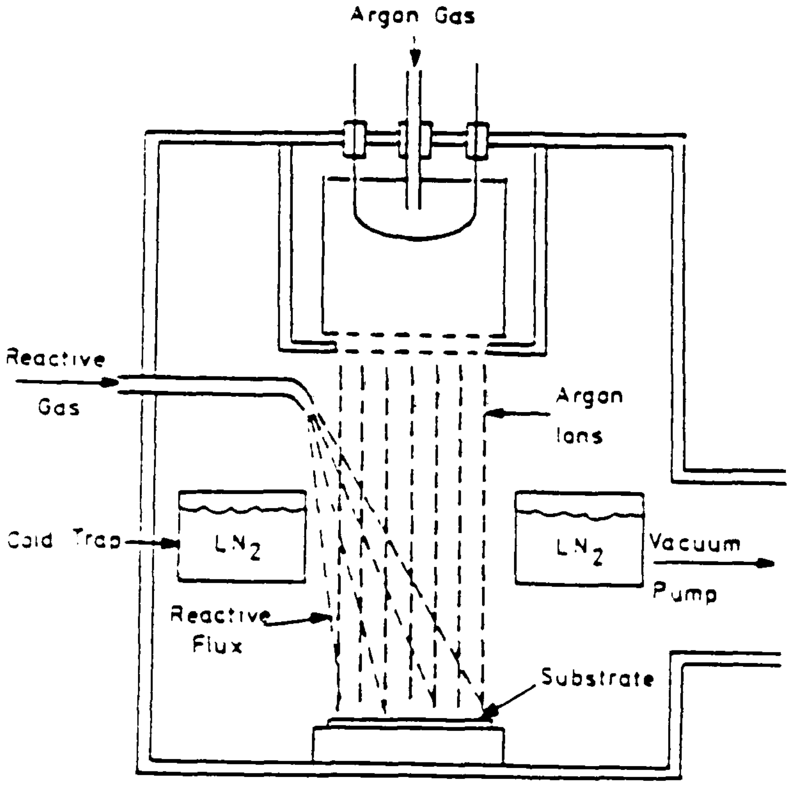

Figure 6. Diagram of the CAIBE system which consists of an ion source, one or more reactive gas jets (only one shown), and a cold trap to pump the unused reactive gas and the reaction products. The stainless steel vacuum chamber is pumped either with a cryopump or a cold trapped diffusion pump. The beam of argon ions is broad-area, collimated, and accelerated to a few hundreds of volts energy. Chlorine, which is the usual reactive chemical for III-V etching is admitted in gaseous form from a jet about 3.5 cm from the sample surface. The chamber is maintained at a vacuum in the 10-4 Torr range while the chlorine flux is equivalent to a pressure of 2x10-2 Torr. Reaction of the chlorine atoms with the surface and removal of the by-products is assisted by the energetic argon ions. (Ref. 33.)

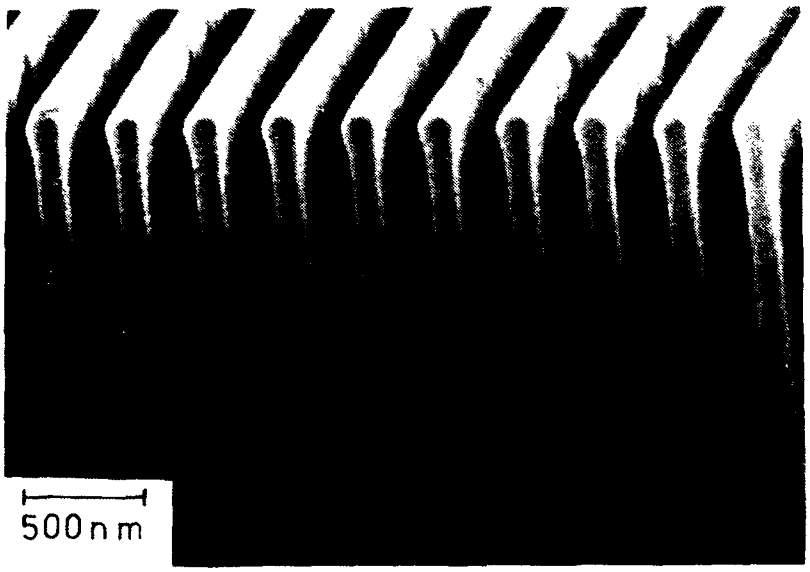

Figure 7. Scanning electron micrograph of a GaAs sample etched by CAIBE. The grating is etched to about 1.5 microns deep.

One of the strongest arguments for a longer wavelength (10 μ) approach to digital optical signal processing, such as QWEST(18), is that the required fractional-wavelength smoothness and dimensional tolerances are now possible whereas, at typical bandgap wavelengths of solid state lasers (around 1 micron), they are not.

V. Equipment & Manpower Needs.

Table 3 is a list of equipment which would be needed for basic fabrication technology, assuming that epitaxial material and masks would be obtained from other laboratories.

Table 3. Equipmont and manpower for basic device fabrication.

	Capital	Staff	
	M$	Prof.	Tech
Lithography			
Contact Optical	0.1		
Spinner, Hoods, Ovens, Etc.	0.1	1	1
Image Reversal	0.1		
Etching			
Chemical Assisted Ion Beam	0.45	1	1
Thin Film Deposition			
E-Beam Evaporators (2)	0.5		
Plasma CVD	0.2	1	1
Annealing	0.1		
Characterization			
Surface Profilometer	0.05		
Optical Microscopes	0.025		
Scribe & Cleave	0.05		
Facilities			
Clean Room & Services	0.75		1
Management			
Group Leader		1	
TOTALS	$2.325M	4	4

A facility based on the equipment and staffing represented in Table 3, plus the scanning electron microscope and Auger microprobe presently available in the Reliability Directorate, would be capable of integrated GaAs photonic circuit fabrication, including waveguides, mirrors, and conductors with dimensions down to about 0.5 micron and edge smoothness sufficient for single mode low loss guiding initially in the 10 micron wavelength range but subsequently extendable to about 3 micron wavelengths. Work would have to be coordinated closely with laboratories able to supply state-of-the-art epitaxial materials. Two key limitations of such an approach should be noted:

(1) Most structures needed will require some fabrication as an intermediate step between epitaxial growth steps. This would require wafers to be shifted back and forth between laboratories at intermediate stages of completion, with resultant inefficiencies and opportunities for contamination.

(2) Certain key structures such as chirped grating couplers will require electron beam lithography. Lithography for gratings with uniform period down to about 250 nanometers can be done with equipment already existing at the Photonic Center but, as pointed out in the discussion of QWEST above, the need for chirped period gratings is already envisioned.

An additional consideration is the desirability of having in-house mask making to enable quicker implementation of new designs. This would also be provided by electron beam lithography. Additional costs and staff requirements needed to provide a complete in-house capability are indicated in Table 4.

Table 4. Major equipment and additional manpower for complete in-house device fabrication.

	Capital M$	Staff Prof	Staff Tech
Crystal Growth & Implantation			
MBE	0.75	1	1
MOCVD	1.5	1	1
Ion Implantation	1.0	1	1
Lithography			
Electron Beam	2.5	1	1
TOTALS	$ 5.75 M	4	4
TAB. 3 & TAB. 4 TOTALS	$ 7.945 M	8	8

VI. Opportunities for University Collaboration

The Air Force Photonics Center is located within one hundred miles of the best university based GaAs growth and fabrication facilities in the country. At Cornell University, the NSF sponsored National Nanofabrication Facility not only has all of the facilities mentioned in Table 3, but it has a charter which explicitly addresses the needs of outside users. Together with MBE and MOCVD growth facilities under Professors L.F. Eastman and R.J. Shealy, respectively, the Department of Electrical Engineering has a complete capability to grow and fabricate state-of-the-art compound semiconductor devices. As mentioned previously, a key approach to optical logic, mode switching in semiconductor lasers, is presently being investigated by C.L. Tang at Cornell under joint NSF and RADC support.

At Syracuse University, a new laboratory is being constructed which may house another complete set of facilities within a couple of years provided funding of the equipment can be found. Professors P. Kornrich and P.K. Ghosh are already involved in collaborative activities with RADC.

At the University of Rochester, MBE facilities are presently being installed by Professor G.W. Wicks, and an extensive program of high speed optical characterization has been developed at the U.R. Laboratory for Laser Energetics by G. Mourou.

Industrial laboratories, notably G.E., IBM, Kodak, Hughes, Honeywell, and Ford Aerospace have made rapid entrances into the compound semiconductor field partly as a result of their interactions with Cornell. Though their intent from the outset was to build their own capability, they have used the avenue of supporting programs at the University as a means of becoming associated immediately with state-of-the-art research, and as an entree to interaction with and finally successful hiring of graduates from the program. Exchanges of personnel have occurred in both directions. Employees have been supported as students and post-Doctoral Fellows at the University while spending summers at the company's facility.

Government labs, when they have been able to offer attractive supplemental or alternate facilities such as the MBE machine at Fort Monmouth, have also attracted students to perform their dissertation research at the government location. University collaboration should be regarded as a valuable boost rather than a long term substitute for an in-house program. The university facilities even when extensive, such as Cornell's, are under the control of many faculty members, are used in support of varying research programs, and tend to be constantly undergoing modification. Thus, while they can be effectively focussed on individual research problems, they cannot provide advanced system hardware development.

VII. Summary, Conclusions and Recommendations.

The purpose of this study is to provide information enabling a decision on whether and to what extent the Photonics Center should assemble and implement a microfabrication capability as part of its research program. The study has focussed on the area of digital optical signal processing, but this has not been because of any lack of applicability of microfabrication to the Center's other areas--analogue processing and microwave bandwidth optical interconnects. Indeed the programs in both of these other areas stand to benefit every bit as much from the presence of an in-house microfabrication capability. Rather the focus on digital optical processing has been because this field is in a state where progress depends almost entirely on developments in the areas of materials and fabrication.

Key findings from this study to date have been that:

(1) Digital optical signal processing is in a primitive stage with many materials and approaches still being examined and no demonstrably satisfactory solutions.

(2) At present, the promising areas for serial architectures seem to be the QWEST effect and mode switched semiconductor lasers. For 2D array architectures, quantum well SEED devices and band filling non-linearities in low bandgap semiconductors such as InSb are the promising areas but the search for improved materials for both types of architecture continues, especially in the area of organics.

(3) A key technology for fabricating etched mirrors required for integrated photonics, chemical assisted ion beam etching, has recently achieved the necessary resolution.

(4) Construction of a digital optical system poses fundamental problems which are unlike those which have been encountered in electronic systems, and which necessitate new architectural approaches.

(5) The cost of microfabrication capabilities would start at $2.5 million for a capability including only optical lithography, thin film deposition, and chemical assisted ion beam etching. Electron beam lithography costing another $2.5 million would provide a more complete capability.

(6) A source for state-of-the-art epitaxial material is essential but it should be noted that epitaxial growth is often an intermediate as well as an initial step in optical device fabrication. Epitaxial growth capability would be $0.75 million for MBE and $1.5 million for MOCVD. One or the other may be sufficient. Ion implantation costing $1 million would be a convenience, but implantation is available as a service.

(7) Staffing needs for microfabrication would range from 8 to 16 depending on choices made in (5), above, with an equal mix of professionals (advanced degrees) and technicians.

(8) Opportunities for university collaboration are excellent. These should be exploited as a means to enter the field rapidly. To do so will require coordination of funding, from other directorates if necessary, to support programs at the universities serving the objectives of photonics. Attracting university personnel to work at the center can be achieved by providing needed equipment at the center.

Taken together with the stated mission of the Photonics Center to meet the Air Force needs through an in-house research program of international stature, the findings of this study suggest that, in the long term as the center begins to produce actual photonic systems, a microfabrication facility will be an essential part of the program.

REFERENCES

(1) P.W. Smith, "Bistable Optical Devices," in New Directions in Guided Wave Optics, Ed. by D.B. Ostrowski and E. Spitz; Martinns Nijoff, Boston (1984) pg. 419.

(2) D.A.B. Miller, M.D. Feuer, T.Y. Chang, S.C. Shunk, J.E. Henry, D.J. Burrows, and D.S. Chemla, IEEE Photonics Technology Letters 1, 62, (1989)

(3) P.W. Smith and E.H. Turner, Appl. Phys. Lett. 30, 280 (1977); P.W. Smith, I.P. Kaminow, P.J. Maloney, and L.W. Stulz, Appl. Phys. Lett. 33, 24 (1978)

(4) "Research on Nonlinear Optical Materials: An assessment", D.H. Auston, A.A Ballman, P. Bhattacharya, G.J. Bjorklund, C. Bowden, R.W. Boyd, P.S. Brody, R. Burnham, R.L. Byer, G. Carter, D. Chemla, M. Dagenais, G. Dohler, U. Efron, D. Eimerl, R.S. Feigelson, J. Feinberg, B.J. Feldman, A.F. Garito, E.M. Garmire, H.M. Gibbs, A.M. Glass, L.S. Goldberg, R.L. Gunshor, T.K. Gustafson, R.W. Hellwarth, A.E. Kaplan, P.L. Kelley, F.J. Leonberger, R.S. Lytel, A. Majerfeld, N. Menyuk, G.R. Meredith, R.R. Neurgaonkar, N.G. Peyghambarian, P. Prasad, G. Rakuljic, Y.R. Shen, P.W. Smith, J. Stamatoff, G.I. Stegeman, G. Stillman, C.L. Tang, H. Temkin, M. Thakur, G.C. Valley, P.A Wolff, and C. Woods, Applied Optics, 26, 211, (1987).

(5) S.S. Yao, C. Karaguleff, A. Gold, R. Fortenberry, C.T. Seaton, and G.I. Stegeman, Appl. Phys. Lett. 46, 801 (1985); P. Roussignol, D. Ricard, K.C. Rustagi, and C. Flytzanis, Opt. Commun. 55, 143 (1985).

(6) D.A.B. Miller, M.H. Mozolowski, A. Miller & S.D. Smith, Optics Comm. 27, 133 (1978); D.A.B. Miller, S.D.Smith, and A. Johnston, Appl. Phys. Lett. 35, 658 (1979); S.D. Smith et al, Opt. Eng. 24, 569 (1985); D.A.B. Miller, C.T. Seaton, M.E. Prise, and S.D. Smith, Phys. Rev. Lett. 47, 197 (1981).

(7) H.M. Gibbs, S.L. McCall, T.N.C. Venkatesan, A.C. Gossard, A. Passner, and W. Wiegmann, Appl. Phys. Lett. 35, 451 (1979).

(8) N. Peyghambarian and H.M. Gibbs, J. Opt. Soc. Am. B 2, 1215 (1985).

(9) F. Capasso and B.F. Levine, J. Lumin. 30, 144 (1985); D.S. Chemla, J. Lumin. 30, 502 (1985).

(10) H. Yokoyama, IEEE Jour. Quant. Electron. 25, 1190 (1989)

(11) Lawrence C. West, "Picosecond Optical Logic," Computer, pg 34, December, (1987).

(12) C.K.N. Patel, R.E. Slusher & P.A. Fleury, Phys. Rev. Lett. 17, 1011 (1966); P.A. Wolff & Gary A. Pearson, Phys. Rev. Lett. 17, 1015 (1966).

(13) C.D. Poole and E. Garmire, IEEE J. Quantum Electron. QE-21, 1370 (1985); Optics Lett. 9, 356 (1984); App. Phys. Lett. 44, 363 (1983)

(14) D. Craig. A.D. Dai, J.G.H. Mathew, and A. Miller, IEEE J. Quantum Electron. QE-21, 1363 (1985).

(15) H.M. Gibbs, A.C. Gossard, S.L. McCall, A. Passner, and W. Wiegmann, Solid State Commun. 30, 271 (1979); D.A.B. Miller, D.S. Chemla, D.J. Eilenberger, P. W. Smith, A.C. Gossard, and W.T. Tsang, Appl. Phys Lett. 41, 679 (1982).

(16) D.A.B. Miller, D.S. Chemla, P.W. Smith, A.C. Gossard, and W.T. Tsang, Appl. Phys. B28, 96 (1982); D.A.B. Miller, D.S. Chemla, D.J. Eilenberger, P.W. Smith, A.G. Gossard, and W. Wiegmann, Appl. Phys. Lett. 42, 925 (1983).

(17) S. Ovadia, H.M. Gibbs, J.L. Jewell, D. Sarid, N. Perghambarian, Optical Eng'g. 24, 565 (1985).

(18) M. Dagenais, Appl. Phys. Lett. 43, 742 (1983); M. Dagenais and W.F. Sharfin, Appl. Phys. Lett. 46, 230 (1985).

(19) S.W. Koch & H. Huag, Phys Rev. Lett. 46, 450 (1981); E Hanamura, Sol. St. Comm. 38, 939 (1981); N. Peyghambarian, H.M. Gibbs, M.C.Rushford, and D.A. Weinberger, Phys Rev. Lett. 51, 1692 (1983); J.Y. Bigot, F.Fidorra, C. Klingshirn, and J.B. Green, IEEE J. Quantum Electron. QE-21, 1480 (1985).

(20) S.Y.Yuen, Appl. Phys. Lett. 43, 479 (1983).

(21) S.Y. Yuen, P.A. Wolff, and L.R. Ram-Mohan & R.A. Logan, Solid State Commun. 56, 489 (1985).

(22) G.R. Olbright, N. Peyghambarian, H.M. Gibbs, H.A. Macleod, and F. Van Milligan, Appl. Phys. Lett. 45, 1031 (1984); S.Y. Yuen and P. Becla, Opt. Lett. 8, 356 (1983).

(23) I. Janossy, M.R. Taghizadeh, J.G.H. Mathew, and S.D. Smith, IEEE J. Quantum Electron QE-21, 1447, (1985).

(24) M. Dagenais and W.F. Sharfin, Appl. Phys. Lett. 45, 210 (1984).

(25) B.S. Wherret, D. Hutchings & D. Russel, J. Opt. Soc. Am. (1986).

(26) D. Craig, A.K. Kar, J. Gordon, H. Mathew & A. Miller, IEEE Jour. Quant. Electron. QE-21, 1363 (1985).

(27) P.A. Wolff, S.Y. Yuen, and G.A. Thomas, Solid State Commun. 60, 645 (1986).

(28) P.A. Wolff, S.Y. Yuen, K.A. Harris, J.W. Cook, and J.F. Schetzina, Appl Phys Lett. 50, 1858 (1987).

(29) S.Y. Yuen, Appl. Phys. Lett. 43, 813 (1983)

(30) L.C. West and S.J. Eglash, Appl. Phys Lett. 46, 1156 (1985)

(31) T. Fujita, A. Schremer, and C.L. Tang, Electronics Lett., July, (1987); T. Fujita, A Schremer, and C.L. Tang, Appl. Phys. Lett. 51, 392, (1987); C.L. Tang, A. Schremer, and T. Fujita, Appl. Phys. Lett. 51, 1392, (1987).

(32) P.W. Smith, Bell Syst. Tech. Jour. 61, pg 1975, (1982).

(33) R. W. Keys, Science 168, 796 (1970).

(34) M.E. Prise, N. Streibl, and M.M. Downs, Optical and Quantum Electronics 20, 49-77 (1988).

(35) A. Huang, To be presented at OSA/IEEE topical Meeting on Optical Computing, Salt Lake City, Feb. 27-March 1, 1989;A. Huang, "Computational Origami" U.S. Patent Pending; H.M. Lu, "computational Origami: A Geometric Approach to Regular Multiprocessing," MIT Master's Thesis in Electrical Engineering, (May, 1988); A. Huang, "Architectural Considerations Involved in the Design on an Optical Digital Computer," Proc. IEEE 72, No. 7 (July 1984).

(36) G.A. Lincoln, M.W. Geis, S. Pang, and N.N. Efremow, J. Vac. Sci. Technol. B 1 (4), 1043 (1983); M.W. Geis, G.A. Lincoln, N. Efremow, and W.J. Piacentini, J. Vac Sci. Technol. 19(4), 1390 (1981)

(37) W.J. Grande, W.D. Braddock, J.R.Shealy and C.L. Tang, Applied Physics Letters 51, 2189 (1987); W.J. Grande, Thesis, Cornell University, 1989.

(38) BIBLIOGRAPHY OF BAND FILLING NONLINEARITY

Year Reference

1986 Switching with Diode Laser Source
H.A. Al-Attar, A.C. Walker, F.A.P. Tooley, & H.A. MacKenzie, "The Gain-Bandwidth of an InSb Transphasor," IEEE J. Quantum Electron. QE-22, May (1986)

1985 DBM in InSb
B.S. Wherrett & S.D. Smith, Eds. Optical Bistability, Dynamical Nonlinearity and Photonic Logic (Royal Society, London, 1985), p. 451

Optical Bistability in InSb
F.A. P. Tooley, A.C. Walker, & S.D. Smith, "The External Switching of Intrinsic Optically Bistable Devices by Incoherent Illumination," IEEE J. Quantum Electron. QE-21, 1340, (1985)

No Slow thermal effects (in InSb)
G.R. Olbright, N Peyughambarian, H.M. Gibbs, H.A. Macleod, & F. VanMilligan, "Microsecond Room-Temperature Optical Bistability and Crosstalk Studies in ZnS and ZnSe Inereference Filters with Visible Light and Milliwatt Powers," Appl. Phys Lett. 45, 10 (1984)

External Switching (InSb?)
W.R. MacGillivray, S.D. Smith, H.A. MacKenzie, & F.A.P. Tooley, "Photonic Logic, the First Step toward the Optical Computer," Opt. Acta 32, 511 (1985)

Switching with a Diode Laser Source
F.A. P. Tooley, W.J. Firth, A.C. Walker, H.A. MacKenzie, J.J. E. Reid, & S.D. Smith, "Measurement of the Bandwidth of an Optical Transphasor," IEEE J. Quantum Electron. QE-21, 1356 (1985).

Comparison of DBM & Excitonic Effects
E. Garmire, "Infrared All-Optical Information Processing in Semiconductors," Opt. Eng. 24, 575 (1985)

Saturation Effects in InAs
C.D. Poole & e. Garmire, IEEE J Quantum Electron. Special Issue on Optical Bistability (Sept. 1985)

Flash Lamp Switching
F.A.P. Tooley, A.C. Walker & S.D. Smith, IEEE J. Quantum Electron., Special Issue on Optical Bistability (Sept. 1985).

C.D. Poole, "Optical Nonlinearities in InAs," PhD Thesis, Univ. Southern Calif (1984)

Year	Reference
1983	Comparisons S.D. Smith, I. Janossy, H.A. MacKenzie, J.G.H. Mathew, J.J.E. Reid, M.R. Taghizadeh, F.A.P. Tooley, A.C. Walker, "Nonlinear Optical Circuit Elements as Logic Gates for Optical Computers: The First Digital Optical Circuits," Optical Engineering, 24, 569 (1985)
	Size of Divice Predicted from Knowledge of Diffusion Length S.J. Hagan, H.A. Mackenzie, H.A. AlAttar, & W.J. Firth, Opt. Lett. 10, 4 (1985)
1984	DBM Effect in InAs C.D. Poole & E. Garmire, "Nonlinear Refraction at the Absorption Edge in InAs," Opt. Lett. 9, 8 (1984)
	Expression for Figure of Merit in DBM C.D. Poole & E. Garmire, Opt. Lett. 9, 356 (1984)
	Optical Bistability in InSb A.C. Walker, F.A.P. Tooley, M.E. Prise, J.G.W. Mathew, A.K. Kar, M.R. Taghizadeh, & S.D. Smith, "InSb Devices: Transphasors with High Gain, Bistable Switches and Sequential Logic Gates," Philos. Trans. R. Soc. London Ser A313, 249-256 London (March 1984)
	F.A.P. Tooley, A.C. Walker, & S.D. Smith, Philos. Trans. R. Soc. London, Proc. Optical Bistability, Dynamical Nonlinearity and Photonic Logic, A 313, 357-360 London (March 1984)
	Change in Reflected Greater then Transmitted B.S. Wherrett, IEEE J. Quantum Electron. QE-20(6), 646 (1984)
1983	Effect of small thermal changes; Indication of possible switching times of a few picoseconds C.T.Seaton, S.D. Smith, F.A.P. Tooley, M.E. Prise, & M.R. Taghizadeh, "Realization of an InSb Bistable Device as an Optical AND Gate and its Use to Measure Carrier Recombination Times," Appl. Phys Lett. 42,2 (1983)
	Response Time of 90 Ns. C.T. Seaton, S.D. Smith, F.A.P. Tooley, M.E. Prise, & M.R. Taghizadeh, Appl. Phys. Lett. 42, 131 (1983)
	DBM in InAs C.D. Poole, & E. Garmire, Appl. Phys. Lett. 44, 363 (1983)

(38) BIBLIOGRAPHY OF BAND FILLING NON-LINEARITY (Cont'd.)

Year	Reference
1982	DBM in InSb D.A.B. Miller, M.H. Mozolowski, A. Miller, and S.D. Smith, "Nonlinear Optical Effects in InSb with a cw CO Laser," Opt. Commun. 27, 000 (1982)
	DBM in HgCdTe J.R. Hill, G. Parry, & A. Miller, "Nonlinear Refractive Indey Caanges in CdHgTe at 175 K with 1016 micron Radiation," Opt. Commun. 43, 151 (1982).
	No rapid thermal effects in InSb J.L. Jewell, H.M. Gibbs, S.S. Tarng, A.C. Gossard, & W. Wiegmann, "Regenerative Pulsations from an Intrinsic Bistable Optical Device," Appl. Phys Lett. 40, 4 (1982).
1981	D.A.B. Miller, C. T. Seaton, M.E. Prise, & S.D. Smith, "Band-Gap Resonant Nonlinear Refraction in III-V Semiconductors," Phys. Rev. Lett. 47, 197 (1981)
	DBM Effect first seen in InSb D.A.B. Miller, S.D. Smith, & C.T. Seaton, IEEE J. Quantum Electron. QE-17, 312 (1981)
1980	Theoretical Explanation T.S. Moss, "Theory of Intensity Dependence of Refractive Index," Phys. Stat. Sol. (b) 101, 555 (1980)
	Written in Parallel with the Moss paper. D.A.B. Miller, S.D. Smith, & B.S. Wherrett, Opt. Commun. 35, 221 (1980)
1979	DBM Effect D.A.B. Miller, S.D. Smith, & A. Johnston, "Optical Bistability and Signal Amplification in a Semiconductor Crystal: Application of New Low-Power Nonlinear Effects in InSb," Appl. Phys. Lett. 35, 658 (1979);
	Optical Transistor with Steady State Gain (DBM) H.M. Gibbs, S.L. McCall, T.N.C. Venkatesan, A.C. Gossard, A. Passner, & W. Wiegmann, "Optical Bistability in Semiconductors," Appl. Phys. Lett. 35, 6? (1979)
1978	Discovery of Giant Optical Nonlinearities in Semiconductors D.A.B. Miller, M.H. Mozolowski, A. Miller, & S.D. Smith, Opt. Commun. 27, 133 (1978)

APPENDIX A--GRATING FABRICATION

The Photonics Center has the necessary optical equipment for constructing a facility for exposing photoresist on any surface on which it is desired to fabricate a periodic array of ridges for use as an optical grating. To construct such a facility, optical elements would be assembled as shown in Figure A1. In this figure, a UV beam from an argon laser is spatially filtered and expanded to about 1.5 inches diameter. The main beam is then split into several branches. The first of these branches simply goes to a precision rotating stage which is to be used in measuring the period of resist pattern for fabricated gratings. The second branch is further split into two branches which are recombined from opposite directions at oblique angles tc the sample surface. Reflection of these two branches from the sample surface creates a periodic interference pattern in a layer of photoresist which has previously been applied to that surface. The pattern is in the form of parallel light and dark lines. After exposure and development of the resist, a grating mask has been formed in the photoresist which can then be used to etch ridges in the sample surface. The period of the resulting grating will be in the submicron range, down to about 2500 A. Measurement of the actual period can be done before etching by placing a sample with its resist grating on the precision rotating stage and measuring the refraction angle of the UV beam. The beam intensity is more than adequate for this determination to be made using a simple flourescence card to locate the refracted beam.

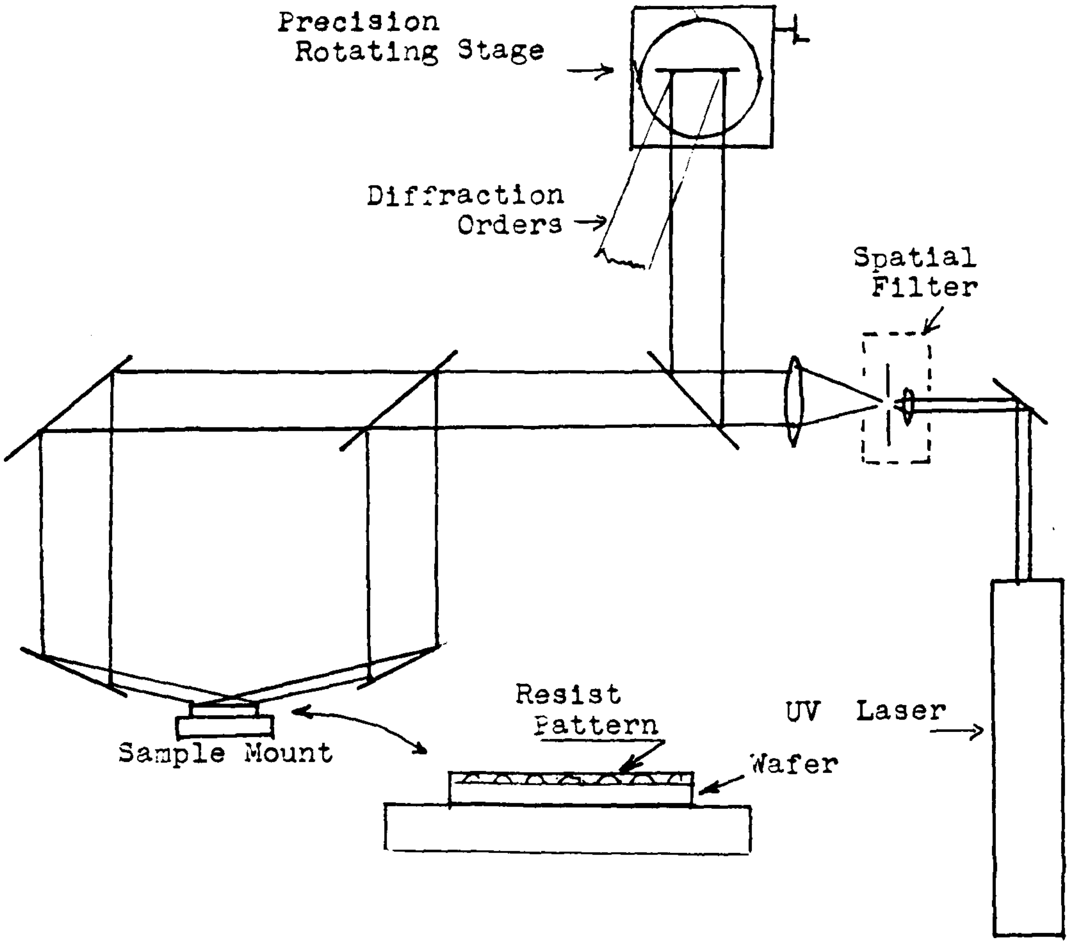

Figure A1. Apparatus for Holographic Grating Exposure

Etching of the grating into the sample surface would have to be done using a "dry" process such as chemical assisted ion beam etching in order to achieve the needed etching precision. A machine for such etching exists, for example, at the National Nanofabrication Facility at Cornell. At present, there is no similar grating exposure system available in the area, so that its construction would supplement available research facilities. Gratings which could be fabricated would be useful for surface emitting lasers, distributed feedback lasers, and surface couplers, all in the 800 nm wavelength range.

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